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PRECISE MEASUREMENT OF THE TEMPERATURE COEFFICIENT OF CAPACITANCE

9 Technical memo

by

10 ISIDORE BADY

11 11 JUNE 1951 12 28 p.

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PRECISE MEASUREMENT OF THE TEMPERATURE COEFFICIENT OF CAPACITANCE

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PRECISE MEASUREMENT OF TEMPERATURE COEFFICIENT OF CAPACITANCE

1. FOREWORD: In many applications, such as in oscillator circuits, tuned circuits, and sweep circuits, it is essential to have capacitors with accurately known and stable temperature characteristics. Hence, many of the specifications on capacitors, such as JAN-C-5 "Capacitors, Mica-Dielectric, Fixed," and JAN-C-20A, "Capacitors, Fixed, Ceramic-Dielectric (Temperature Compensating)" have requirements as to temperature coefficient of capacitance. Equipment to measure temperature coefficient of capacitance so as to determine compliance with the specifications has been constructed in the Component and Materials Branch and is described in the Signal Corps Engineering Laboratories Technical Memorandum M-1165 titled "Equipment to Measure the Temperature U4910 Coefficient of Capacity." With this equipment it is possible to measure capacitance changes due to temperature with an accuracy of 0.015 micromicrofarads.

Though the present equipment is satisfactory for checking specification requirements, it was generally felt that it was necessary to develop still more accurate equipment to measure temperature coefficient of capacitance. For one thing, the tolerances on temperature coefficient are quite broad. For example, in JAN-C-20A, "Capacitors, Fixed, Ceramic Dielectric (Temperature Compensating)," the narrowest tolerance on the temperature coefficient of capacitors with capacitances of less than 51 micromicrofarads is (approximately) ± 60 parts per million per degree centigrade. This is actually so broad a tolerance as to be useless in many applications. However, there was no point to putting narrower tolerances in the specifications till equipment had been developed to make possible more accurate measurements. In addition, research in the development of more stable temperature compensating capacitors was being handicapped for lack of more precise equipment to measure temperature coefficient of capacitance. In the case of low value capacitors, the temperature characteristics of the finished capacitor may be considerably different from that of the ceramic body of which it is made, due to the effect of the added paints and other protective materials. However, it had not been possible to measure this effect due to the lack of adequate test equipment.

In view of the above, work was initiated within the Component and Materials Branch to develop more accurate equipment to measure temperature coefficient of capacitance. The goal was to achieve an accuracy of 0.001 micromicrofarads in the measurement of capacitance increments over any temperature interval between -55°C and 85°C. Only six samples at a time were to be measured. However, it was subsequently decided to greatly expand these goals; namely, to increase the accuracy of measuring increments of small capacitors to 0.0001 micromicrofarads and to extend the temperature range to cover -70°C to 250°C. Also, all this was to be done on a production basis, so that the temperature coefficient of capacitance of 100 capacitors could be measured in one day. In order to achieve these goals as soon as possible, a contract was awarded to New York University on August 1950 to study the whole problem and develop practical means of achieving the desired goals.

The major portion of the work described in this Technical Memorandum was accomplished before the award of the above contract.

2. SUMMARY: Sources of errors in the measurement of temperature coefficient of capacitance are discussed. The most important source of error is in the sample holder. The addition of a shield around the "high" contacting spring greatly reduces errors due to the sample holder and makes it possible to measure increments of capacitance over the range of -55°C to 85°C with an accuracy of 0.001 micromicrofarads. A technique for the automatic measurement of temperature coefficient of capacitance is also described.

3. DISCUSSION:

a. Sources of Errors in the Measurement of the Temperature Coefficient of Capacitance:

(1) Description of Method of Measurement: In order to discuss errors in the measurement of temperature coefficient of capacitance, it is first necessary to describe the method of measurement used, since different methods of measurement may involve different types of errors. The following is a brief description of the method of measurement used in the Performance Test Section, Components and Materials Branch, when an extremely high degree of accuracy is not required. A more complete description is contained in the Signal Corps Engineering Laboratories Technical Memorandum M-1165, titled "Equipment to Measure the Temperature Coefficient of Capacity."

Figure 1 shows a functional diagram of the test equipment. The parts associated with tube T2 compose a one megacycle crystal oscillator. The parts associated with tube T1 compose a variable oscillator designed to operate at 100 kilocycles. The total capacity required in the tank circuit to produce a frequency of 100 kilocycles depends on which coil is chosen by switch S. The capacitor C1 is a variable capacitor used for adjustments. The capacitor C2 represents the standard capacitors actually used in the measurements, and includes a continuously variable capacitor which can read small capacitance increments, such as the General Radio type 722D Precision Condenser, and a set of decade capacitors. The two oscillators and the standard capacitors are maintained at a constant temperature during the test.

The test procedure is as follows: The variable temperature cabinet is set at 25°C and the blank position of the sample holder connected to the tank circuit of the variable oscillator. The standard capacitors C2 are set at a convenient initial setting, and the capacitor C1 is adjusted till the frequency of the variable oscillator is a little higher than 100,000 cycles. The tenth harmonic of this frequency beats against the one megacycle crystal oscillator to produce an audio beat note, which is applied to a pair of plates of an oscilloscope. An audio oscillator is connected to the other pair of plates of the oscilloscope, and when its

frequency is equal to the beat note frequency, the Lissajous figure on the oscilloscope will be a stationary ellipse.

(NOTE: In Technical Memorandum M-1165 there is a discussion of means taken to supress Lissajous figures due to subharmonics of one megacycle other than 100,000 cycles.)

The sample holder is now rotated till the first test capacitor is connected to the variable oscillator. The standard capacitors are decreased till the frequency of the variable oscillator is a little higher than 100 kilocycles and a stationary ellipse is produced on the oscilloscope. The capacitance of the test capacitor at 25°C is equal to the difference between the initial and final settings of the standard capacitors. The capacitance of the other test capacitors at 25°C are similarily measured. This procedure is repeated at all the test temperatures. The same initial setting of the standard capacitors, C2, is used at all times, and the changes in capacitance of the test capacitors, as the temperatures is varied, can be readily computed from the changes in the final settings of C2.

It is apparent that while waiting for the temperature to change and stabilize, oscillator drifts, changes in lead capacitance, and similar changes in components other than the standard capacitors, will cause no errors. It is however important that these changes do not occur during the period when measurements are actually being made at a given temperature. The effect of these changes at the end of the measurement period can be determined by resetting the sample holder to the blank position, and determining by how much, if at all, the setting of the standards required to produce the stationary ellipse differs from the setting of the standards at the beginning of the measurement period. If there has been an appreciable change, it is necessary to repeat all measurements made since the previous setting of the blank position. The frequency with which the blank position should be checked will depend on the stability of the oscillator and on the accuracy desired.

(2) Errors Due to the Sample Holder: In the equipment described in Technical Memorandum M-1165, the principal source of error in measuring small capacitance increments was the sample holder. This error occurred because the sample holder had fairly large stray capacitances and because of imperfect resetability due to mechanical imperfections.

Photographs of the two samples holders described in TM M-1165 are shown in Figures 2, 2A, and 3. The sample holders have 24 and 25 positions respectively. Figure 4 is a drawing of the sample holder in Figure 3, showing its construction.

It is of course desirable when connecting a position on the sample holder to the variable oscillator, that the only capacitance that gets connected to the variable oscillator is that due to the test capacitor. However, there are also stray capacitances associated with the binding posts that are unavoidably connected. Figure 5 illustrates some of the stray capacitances associated with the binding posts. For convenience, only six positions are shown. Each position of the sample holder has one stray capacitance of the type C1 and two stray capacitances of the type C12. In the case of the sample holders shown in Figures 2 and 3, the value of stray capacitances of the type C11 is about 1.3 micromicrofarads. The contribution of a stray capacitance of the type C12 depends on whether or not a test capacitor is connected to the corresponding adjacent position. In Figure 5, the stray capacitance C12 contributes 0.4 micromicrofarads to the capacitance of position 1, since position 2 is substantially at ground potential due to the fact that a test capacitor is connected to position 2. However, the stray capacitance C61 contributes less than 0.05 micromicrofarads to the capacitance of position 1 since it is "floating," and not connected to either the high or ground side of the variable oscillator.

If the stray capacitances associated with the positions had a zero temperature coefficient, they would cause no error at all. If, as the temperature was changed, the stray capacitance of one position changed by the same amount as the stray capacitance of any other position, there would again be no error. However, it is very possible that the stray capacitance of one position will change by an amount that is different from the amount the stray capacitance of some other position will change, and this will cause an error.

There are several reasons as to why the stray capacitances of the various positions may change by different amounts. One reason is that the mycalex disc (see Figure 4) may not be completely uniform. Another is that as the temperature cabinet is cycled through the low temperatures moisture may condense on portions of the mycalex disc, changing its dielectric constant considerably. The distribution of the moisture is very likely to vary over the mycalex disc, and may cause large errors. However, the problem of moisture condensation can be effectively eliminated by preventing leaks in the temperature cabinet and placing silica gel inside.

The stray capacitances described above and illustrated in Figure 5 are fixed capacitances, and at a given temperature will not change no matter how many times a given position is connected to the variable oscillator. However, there is another type of stray capacitance which may cause errors, and this is due to

mechanical imperfections in the sample holder assembly and the contactor springs (primarily the "high" contactor spring). There is an unavoidable amount of slop in the fitting of the shaft in its bearings. Also, the contactor springs may be distorted in one direction or another depending on the direction of rotation of the sample holder, and the amount of distortion may depend on the speed of the movement. Hence, there is a small variation in the stray capacitance of a position each time it is connected to the variable oscillator. This is called imperfect resettability and is, of course, a source of error.

Due to mechanical imperfections, the mycalex disc (see Figure 4) is not completely horizontal, and some parts will be higher than others. Hence, the height of the "high" contactor spring, and the stray capacitance associated with it, will be different for the various positions. This will cause no error if these stray capacitances remain constant or all change by the same amount as the temperature is changed. However, they might not all change by the same amount since, as the temperature is changed, the shaft, the bearings, and the mycalex disc, may become somewhat distorted or shift.

It is not possible to separate out the separate contribution of each of the factors discussed. However, the following experiment was performed to determine the composite error due to the sample holder. All the odd positions of the sample holder shown in Figure 2 were shorted with apiece of wire. Position 24 was taken as the reference position, and the differences between the capacitance of position 24 and the capacitances of each of the other even positions were measured. These measurments were repeated 4 times at room temperature. The temperature was lowered to $-55°C$, and again 4 sets of measurements were made. The temperature was raised to 85°C and again 4 sets of measurements were made. The test results are shown in Table I below:

Table I

Differences in Capacitance Relative to Position 24

(All Capacitance differences are given in thousandths of a Micromicrofarad)

	25°C				-55°C				85°C				
24	–	–	–	–	–	–	–	–	–	–	–	–	–
2	-45	-45	-47	-47	-47	-48	-48	-47	-47	-50	-47	-50	5
4	-47	-47	-49	-47	-44	-43	-45	-43	-40	-43	-40	-42	9
6	-21	-21	-22	-20	-24	-20	-22	-21	-19	-16	-14	-14	10
8	13	13	12	13	13	13	11	12	11	13	13	13	2
10	13	14	14	15	15	17	15	16	12	13	11	12	6
12	-36	-35	-34	-34	-34	-34	-36	-34	-36	-35	-33	-33	3
14	-37	-34	-34	-35	-33	-33	-33	-33	-36	-39	-39	-39	6

	25°C				-55°C				85°C				
16	-21	-21	-22	-19	-20	-20	-21	-23	-19	-18	-18	-19	5
18	-12	-10	-12	-14	-15	-14	-15	-16	- 8	- 7	- 7	- 8	8
20	-56	-54	-55	-55	-58	-57	-59	-59	-52	-51	-53	-53	8
22	-75	-75	-75	-77	-78	-75	-77	-76	-71	-72	-70	-72	8

Similar results were obtained when the even positons were shorted and the odd positions measured. Similar results were also obtained with the sample holder shown in Figure 3.

On the basis of the above data, the error due to the stray capacitances and imperfect resettability of the sample holder was taken as 0.01 micromicrofarads.

The errors due to the sample holder were the limiting factors in the accuracy of measurement with the equipment described in Technical Memorandum M-1165. There was no point to improving further other such factors as oscillator stability or accuracy of reading capacitance increments due to the magnitude of the errors in the sample holder.

(3) Errors in Reading Capacitance Increments: The most significant error in reading capacitance increments is the magnitude of the smallest increment that can be read accurately. With the equipment described in Technical Memorandum M-1165, the General Radio Precision Condenser was most generally used. The capacitance difference per dial division on the "Low" range of this capacitor is 0.02 micromicrofarads. Capacitance differences could be reliably read to the nearest 0.01 micromicrofarads. When it was necessary to read smaller capacitance increments the "adjusting" capacitor C1 was used as the "standard" capacitor, and the capacitor C2 used to make adjustments. The capacitor C1 is a straight line frequency capacitor, and at its low capacitance end, capacitance differences can be reliably read, with the aid of a vernier, to the nearest 0.002 micromicrofarads.

(4) Errors Due to Oscillator Instability: As discussed in Section 3a(1) above, only a short time stability is required of the oscillator. The drift of the oscillator must not be appreciable during a measurement period. A measurement period may last from a half minute up to several minutes, depending on how many capacitors are measured in between checks of the blank position. What constitutes an "appreciable" drift in the oscillator depends of course on how accurately the capacitance increments are being measured. With the test equipment described in Technical Memorandum M-1165, capacitance increments were generally measured to the nearest 0.01 micromicrofarads for small test capacitors and to the nearest 0.1 micromicrofarads for large test capacitors. In both cases the oscillator stability was adequate and at least six capacitors could be measured at one time without an apprecialbe oscillator drift occurring.

(5) Other Sources of Errors: There are of course other sources of errors, such as lead inductance, change of Q of the test capacitors, temperature gradients, and not perfectly stable temperature control in the variable temperature cabinet. These factors are discussed in Technical Memorandum M-1165. However, they will not be considered further here, as it is the purpose of this report to concentrate on the sources of errors discussed in Sections 3a(2), 3a(3), and 3a(4).

b. Means Taken to Reduce Errors in the Measurement of Temperature Coefficient of Capacitance:

(1) Reduction of Errors Due to Sample Holder.

A drawing of a new sample holder designed to greatly reduce errors due to the sample holder is shown in Figure 6. A photograph of the sample holder is shown in Figure 7. One feature of this sample holder is that the stray capacitance of the "high" positions was greatly reduced. The stray capacitance of the type C11 (see Figure 5) was reduced by cutting out large segments of mycalex in front of the position, and by decreasing the size of the binding post used. The stray capacitance of the type C12 was reduced by having fewer positions on the sample holder thus increasing the space between the positions.

The main feature in the new sample holder is the addition of a shield which is directly connected to the "high" contactor spring. The location of the shield in relation to the sample holder can be seen in Figures 6 and 7. A close up photograph of the shield is shown in Figure 8. This shield serves as a partial Faraday shield. The inside of the shield is substantially at constant potential, and hence the effect of movement of the "high" binding posts on the stray capacitance of the system is far less than it would be if the shield were absent. That is, the "high" binding post of the position connected to the tank of the oscillator can be pushed a little up or a little down, a little to the left or a little to the right, without effecting the stray capacitance of the system appreciably. Also the contactor springs can be distorted considerably without effecting the stray capacitance appreciably. The above two sentences are of course qualitative. However, the following illustrates the effectiveness of the shield. With a given position connected to the oscillator, the decrease in capacitance due to removing the "high" binding post was only 0.04 micromicrofarads. A similar measurement made with the shield removed, gave a change of about 1.0 micromicrofarad.

The total stray capacitance associated with a position is more than the 0.04 micromicrofarads mentioned above. The total stray capacitance associated with a given position was measured by noting the decrease in capacitance resulting when the mycalex disc was removed. This amounted to 0.25 micromicrofarads. The bulk of this stray capacitance is due to the presence of the mycalex in the field set up by the capacitance of the shield to ground. The thickness of the mycalex is only a small portion of the path of the "lines of force" that go from the shield to ground through the mycalex. Most of the path is through air. In such a case, changes in the dielectric constant of the mycalex (due to temperatures changes, absorption of moisture, or other causes) cause much smaller changes in the stray capacitance than would occur if the path of the "lines of force" was principally through the mycalex, as exemplified by the stray capacitance illustrated in Figure 5. This is demonstrated in the Appendix.

The new sample holder was checked to determine the error it would cause in the measurement of capacitance increments, in a manner similar to that used with the older sample holders. (See Section 3a(2)). In this case it was not necessary to short circuit alternate positions since the positions in the new sample holder were separated by considerably larger space than in the older sample holders. Test results are shown in Table II. The variable temperature chamber was cycled several times in order to establish firmly the characteristics of the new sample holder.

Table II

Differences in Capacitance Relative to Position 1

(All Capacitance Differences Given in Thousandths of a Micromicrofarad)

Position	(1) 25°C				(2) 85°C				(3) 25°C			
1	-	-	-	-	-	-	-	-	-	-	-	-
2	11.3	10.8	11.3	11.3	11.3	10.8	10.8	10.8	10.8	11.3	10.8	11.0
3	14.5	14.5	15.0	15.0	15.0	15.0	15.0	15.0	14.8	15.0	14.3	14.5
4	8.0	8.0	7.8	7.8	7.8	8.3	7.8	7.3	7.8	7.8	7.5	7.3
5	5.5	5.5	5.3	5.0	5.0	5.5	4.3	4.3	5.3	4.8	5.3	4.8
6	4.3	4.3	4.0	4.3	4.5	4.0	4.3	4.0	4.8	3.8	4.8	3.8
7	2.8	3.0	2.5	2.5	3.5	2.8	2.8	2.5	2.8	2.3	2.8	2.8

Position	(4) -55°C				(5) 85°C				(6) 25°C			
1	-	-	-	-	-	-	-	-	-	-	-	-
2	11.0	10.8	10.8	10.8	11.3	11.3	11.0	10.8	11.3	11.0	11.0	10.8
3	14.5	14.5	14.3	14.3	15.0	14.8	15.0	15.0	14.5	14.5	14.8	14.8
4	7.5	7.5	7.5	7.8	7.3	7.8	7.5	7.5	7.0	7.0	7.5	7.5
5	5.0	5.3	5.0	5.3	4.8	4.5	4.8	4.5	4.8	4.5	5.0	5.0
6	4.3	4.5	4.3	4.5	4.3	4.0	4.0	4.0	3.8	4.3	4.5	4.5
7	3.0	2.8	2.5	2.5	2.8	2.8	2.5	2.5	2.5	2.5	2.8	2.5

Position	(7) 85°C				(8) -55°C				(9) 25°C			
1	-	-	-	-	-	-	-	-	-	-	-	-
2	10.8	11.3	11.3	11.0	10.5	10.5	10.5	10.3	10.8	10.8	10.8	10.8
3	14.8	15.3	15.3	14.8	14.0	14.0	14.5	14.3	14.3	14.5	14.3	14.5
4	7.5	7.5	7.3	7.3	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
5	4.8	4.5	4.8	4.5	5.0	4.8	5.0	4.8	4.5	4.5	4.8	4.5
6	4.0	4.5	4.0	4.3	4.0	4.3	4.0	4.0	4.0	3.8	4.0	4.0
7	2.5	3.3	2.5	2.8	2.8	2.3	2.5	2.8	2.3	2.3	2.8	2.5

Position	Maximum Spread in Readings
1	-
2	1.0
3	1.3
4	1.3
5	1.3
6	1.0
7	1.3

Thus with each position measured a total of 36 times, the greatest spread (or discrepancy) between any pair of readings of any position was only 0.0013 micromicrofarads. If at each temperature, the average of the four readings at each position is taken, the maximum spread in the averages for any position is 0.0008 micromicrofarads. It is thus safe to take the maximum error due to the sample holder as 0.001 micromicrofarads. Thus the error due to the new sample holder is decreased to one tenth the error due to earlier sample holders.

The error in the measurement of capacitance increments due to the new sample holder is quite small. However, it is believed that this error can be reduced still further by a better mechanical design of the sample holder and its mechanism. For one thing, the mycalex disc is 12 inches in diameter, but the diameter of the bearing on which it rests is only 2 inches. A redesign of this factor alone will probably improve the accuracy a good deal. It is likely too that a choice of another material that is less effected by moisture than is mycalex, will also improve the accuracy of the measurement.

(NOTE: The new sample holder has a different type of spring contacting mechanism than the older sample holders. This however is not regarded as significant.)

(2) <u>Improvement of Oscillator Stability</u>: There has been considerable progress lately in the art of producing highly stable variable L-C oscillators. Two, such oscillators are the Franklin Oscillator and the Clapp Oscillator. In both circuits, the main feature is the isolation of the tube parameters from the tank circuit. A Franklin Oscillator was built at the Performance Test Section and proved to be very stable when by itself and not connected to the rest of the equipment used in measuring the temperature

coefficient of capacitance. In one minute, the frequency drifted by an amount such as would be caused by a change of capacitance of 0.0001 micromicrofarads. When the equipment to measure temperature coefficient of capacitance was connected to it, and the variable temperature cabinet kept at room temperature, the stability fell off slightly. However, when the variable temperature cabinet was maintained at 85°C or -55°C, the stability fell off considerably. The drift at these temperatures was somewhat erratic. In order to make accurate measurements it was necessary to return to the reference position after only one or two positions were measured.

The relative instability of the oscillator when the variable temperature cabinet was at other than room temperature was most likely due to the fact that when the variable temperature cabinet was set at some temperature, say 85°C, it didn't stay put at one fixed temperature but rather cycled plus or minus some amount (about 1/2°C in this case) about the mean.

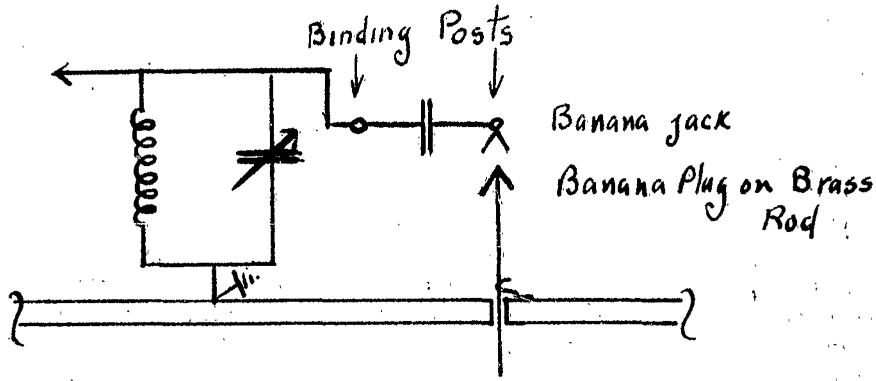
About one foot of the polyethelene cable which was used to connect the sample holder to the tank circuit was inside the variable temperature cabinet. The capacitance of this cable (about 30 micromicrofarads) was part of the tank circuit capacitance, and since its capacitance varied due to the temperature cycling, the oscillator was to that extent unstable.

The ways to increase the stability of the oscillator when the variable temperature cabinet is at other than room temperature, would be to decrease the cycling range of the variable temperature cabinet, design a low capacitance and stable lead between the sample holder and the oscillator to take the place of the polyethelene cable, and keep the length of that lead to a minimum. Consideration should also be given in designing the shield to making its capacitance to ground low and stable.

(3) Improvement in the Reading of Small Capacitance Increments: In order to read very small capacitance increments, the capacitors represented by C2 in Figure 1, and consisting of the General Radio Precision Condenser type 722D and a set of decade capacitors, were replaced by one variable capacitor and one fixed capacitor. The variable capacitor is a specially built capacitor. Its gear drive and dial is exactly the same as that of the main tuning capacitor used in the Frequency Meter BC-221. However, its plates are straight line capacitance instead of straight line frequency as in the capacitor in the BC-221. There are only 4 stationary plates and 3 rotor plates. The difference between the maximum and minimum capacity of this capacitor is about 19 micromicrofarads and over the linear portion of the capacitor, the capacitance per dial division is 0.004 micromicrofarads. With the aid of the vernier, readings can be made and repeated

to the nearest 0.0004 micromicrofarads. It is believed that by reducing the number of plates, the capacity per dial division can readily be reduced by a factor of 4 or more.

The fixed capacitor is a zero temperature coefficient capacitor whose capacitance is equal or close to the nominal value of the capacitors to be tested. It is mounted on two binding posts behind the front panel of the test set, as shown in the sketch below.



A large opening (with a cover provided, of course) has been cut in the panel so that the fixed capacitor can readily be changed. One binding post is connected to the "high" side of the variable oscillator and the second to a banana jack. The banana jack can be shorted to ground by means of a banana plug mounted on a brass rod that is inserted through an opening in the front of the panel. As the brass rod is inserted, a spring, connected to ground, makes contact to the brass rod. The Faraday shield principle is used here, too, and the resettability is virtually perfect.

The test procedure is now as follows: When the sample holder is at the reference position, the brass rod is inserted and thus the fixed capacitor is placed in the tank circuit of the variable osciallator. The special variable capacitor is set at midpoint, and the capacitor C1 (see Figure 1 and Section 3a(1)) adjusted to give the desired test frequency. When the sample holder is connected to one of the positions containing a test capacitor, the brass rod is removed, thus disconnecting the fixed capacitor from the tank circuit. The variable capacitor is then increased or decreased till the original test frequency is obtained. This prodcedure is followed at all test temperatures. The changes in capacitance of the test capacitors as the temperature is changed can be calculated from the changes in the final settings of the special variable capacitor.

c. Proposed Technique for Automatic and Rapid Testing of Temperature Coefficient of Capacitance.

The following proposed technique has not been tried out. However, it seems very promising, and if it works out it will be possible to perform the entire measurement of temperature coefficient of capacitance automatically. That is, the operator will connect the samples to the sample holder, make a single adjustment, press a button, and return in several hours to pick up a sheet on which the test data has been printed by the test set. A small amount of simple arithmetic will suffice to convert the test data to temperature coefficient of capacitance.

A schematic diagram of the proposed technique is shown in Figure 9. A Hartley Oscillator is shown for convenience, though in practice a more stable oscillator such as the Franklin Oscillator or Clapp Oscillator (see Section 3b(2)) should be used. C1 is an uncalibrated adjusting capacitor, which is used to adjust the test frequency. C2 is a zero temperature coefficient capacitor with a capacitance equal to the nominal capacitance of the test capacitors. The frequency counter is a device which has only recently appeared on the market. It can measure any frequency from zero to 10 megacycles per second within an accuracy of 1 part in a million or one cycle. It measures frequency by counting the number of cycles that occur during a set time interval, 10 seconds, 1 second, 0.1 second, or any other interval. The time interval is precisely set by a crystal oscillator and gating circuits. At present, the frequency may be displayed by neon bulbs, or meters (one meter for each decade), or rotating dials (one dial for each decade). However, it would seem to be a relatively simple thing to have the frequency printed on a chart.

The procedure would be as follows: The operator mounts the test capacitor on the sample holder, connects capacitor C2 in its place, and sets the sample holder to its blank position. The sample holder and the switch to capacitor C2 are interconnected (by electrical means or mechanical means) in such a manner that when the sample holder is in its blank position, the capacitor C2 is connected into the circuit. At all other positions, the capacitor C2 is out of the circuit. The operator adjusts C1 so that the desired test frequency is obtained and printed (accurate to one part in a million, or one cycle) on the test data chart. The operator presses a button. The sample holder is automatically rotated to test position 1. When the sample holder is in position, an automatic control causes the frequency counter to measure the frequency and print this value on a chart. The sample holder is then automatically rotated to the next position and again the resulting frequency is automatically printed on the chart. This process is repeated till all test positions have been measured. The frequency at the blank position (with C2 in the circuit) is again measured as a check on the drift of the oscillator.

All the above has been at room temperature. After the blank position has been measured a second time, automatic temperature control equipment which has been preset to bring the variable temperature cabinet to the desired test temperatures in proper sequence, takes the variable temperature cabinet to the first test temperature. When temperature stability has been reached, the measurement process is automatically set into operation. When the measurement has been completed at this temperature, the temperature control equipment automatically takes the variable temperature cabinet to the next temperature, and the entire process repeated. This is continued till the entire test is completed.

In the appendix there is a brief discussion of the calculation procedure used in converting the frequency readings to capacitance increments.

The basic feature of the above system is that it is automatic. However, apart from its being automatic, there is another important feature in which this system differs from that described in Section 3a(1). In the system described in this Section, the sample holder needs to stay in a given position only one or two seconds, since that is all the time that is necessary to measure and print a frequency. However, in the system described in Section 3a(1), the sample holder needs to stay in a given position considerably longer since it takes much longer than 2 seconds to adjust the variable capacitor to secure the desired stationary ellipse, note the setting of the capacitor, and write it down. In the case testing is done manually, the savings in time is important not so much in the overall testing time saved, but in that the stability requirement on the variable oscillator is correspondingly less severe. The disadvantage of the frequency measuring technique is that additional calculation is required.

4. ACKNOWLEDGMENT:

The technique for the automatic and rapid testing of temperature coefficient of capacitance described in section 3 c was conceived by the author during a meeting attended by Proj. J. Mulligan, Prof. P. Greenstein, and Mr. J. S. Smith, all of New York Universtiy, and Mr. J. Conner, and Mr. D. Troxel, of the Naval Research Laboratory, and the author. During this meeting, all aspects of the problem of measuring temperature coefficient of capacitance were discussed, and the author wishes to acknowledge that the groundwork for the idea was developed in the course of the discussion in which all participated.

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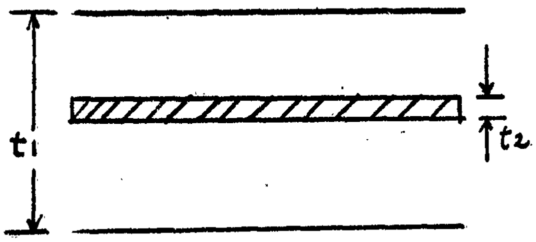
APPENDIX

1. Change in Stray Capacitance Due to Change in the Dielectric Constant of Mycalex in the Case of the New Sample Holder

In the text (section 3b(1)) it is stated that changes in the dielectric constant of the mycalex in the sample holder is smaller in the case of the new sample holder than in the older ones, since in the new sample holder the "lines of force" go principally through air and go only for a short distance through the mycalex. It would not be practical to prove this for the exact geometry involved in the actual sample holder. However, the following example illustrates the principle.



Let C1 be the capacitance of the air capacitor shown to the left before the slab of dielectric (with a dielectric constant of K) is inserted, and C2 the capacitance after it is inserted.

$$C_1 = \frac{B}{t_1}$$

$B = .225\,A$. A is area of one of the electrodes. All dimensions are in inches.

$$C_2 = \frac{\frac{B}{t_1 - t_2} \times \frac{BK}{t_2}}{\frac{B}{t_1 - t_2} + \frac{BK}{t_2}} = \frac{BK}{Kt_1 + t_2(1-K)}$$

$$C_2 - C_1 = \frac{B}{t_1}\left(\frac{K}{K + \frac{t_2}{t_1}[1-K]} - 1\right)$$

$$= \frac{B}{t_1}\,\frac{\left[\frac{t_2}{t_1}(K-1)\right]}{K + t_2/t_1(1-K)}$$

If t2 is considerably smaller than t1,

$$C_2 - C_1 \approx \frac{t_2}{t_1}\left(\frac{K-1}{K}\right)$$

This shows that the change of capacitance is relatively insensitive to changes in dielectric constant. Suppose K were initially 5 and increased by 20% to 6.

$$(C_2 - C_1)_{K=5} = \frac{t_2}{t_1}\,\frac{4}{5} = 0.8\,\frac{t_2}{t_1}$$

$$(C_2 - C_1)_{K=6} = \frac{t_2}{t_1}\,\frac{5}{6} = 0.835\,\frac{t_2}{t_1}$$

Thus a 20% increase in the dielectric constant caused only a 4 1/2% increase in the stray capacity.

2. Calculation of Capacitance Increments From Frequency Readings

Let us consider first that the variable temperature cabinet is at its initial room temperature. Let C be the total oscillator capacitance when the reference position is connected to the circuit. This capacitance includes C1 and C2, (see Section 3c) as well as all lead, jig, and other stray capacitances. Let us assume that C1 has been adjusted so that the desired frequency has been obtained. Let ΔCa be the amount that the first test capacitor differs from C2, and let ΔFa be the change in frequency when this capacitor is connected to the circuit instead of C2.

At the first test temperature after room temperature let $\Delta Co1$ be the amount by which the capacitance of the leads has changed and $\Delta Fo1$ be the frequency when the reference position (and C2) is connected to the circuit. Let $\Delta Ca1$ be the amount that the first test capacitor has changed due to the temperature change, and let $\Delta Fa1$ be the frequency when this capacitor is connected to the circuit. We desire, of course, to determine $\Delta Ca1$ from the measured values ΔFa; $\Delta Fo1$ and $\Delta Fa1$.

$$C = \frac{1}{4\pi^2 L F^2}$$

$$c + \Delta C_a = \frac{1}{4\pi^2 L (F + \Delta F_a)^2} = \frac{C}{\left(1 + \frac{\Delta F_a}{F}\right)^2}$$

$$\approx C\left(1 - 2\frac{\Delta F_a}{F} + 3\left(\frac{\Delta F_a}{F}\right)^2\right)$$

$$\frac{\Delta C_a}{C} = -\frac{2\Delta F_a}{F} + 3\left(\frac{\Delta F_a}{F}\right)^2$$

Similarily

$$\frac{\Delta C_{01}}{C} = -\frac{2\Delta F_{01}}{F} + 3\left(\frac{\Delta F_{01}}{F}\right)^2$$

$$\frac{\Delta C_a + \Delta C_{01} + \Delta C_{a1}}{C} = -2\frac{\Delta F_{a1}}{F} + 3\left(\frac{\Delta F_{a1}}{F}\right)^2$$

$$\frac{\Delta C_{a1}}{C} = \frac{2}{F}\Big\{(\Delta F_a + \Delta F_{01} - \Delta F_{a1}) - \frac{3}{2F}\left[(\Delta F_a)^2 + (\Delta F_{01})^2 - (\Delta F_{a1})^2\right]\Big\}$$

$$\frac{\Delta C_{a1}}{C} = \frac{2}{F}\left[(\Delta F_a + \Delta F_{01} - \Delta F_{a1}) - \frac{3}{2F}\left([\Delta F_a + \Delta F_{01}]^2 - (\Delta F_{a1})^2\right]\right. + 6\frac{\Delta F_a}{F} \times \frac{\Delta F_{01}}{F}$$

$$= \overbrace{\frac{2}{F}(\Delta F_a + \Delta F_{01} - \Delta F_{a1})}^{a}\overbrace{\left(1 - \frac{3}{2F}[\Delta F_a + \Delta F_{01} + \Delta F_{a1}]\right)}^{b} + \underbrace{6\frac{\Delta F_a}{F} \times \frac{\Delta F_{01}}{F}}_{c}$$

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The above expression appears to be quite formidable. However, in a large majority of cases, only the term "a" will be of any significance. The term "b" will in most practical cases be close enough to unity to be disregarded, and the term "c" will be so much smaller than "a", that it too can be disregarded.

If the measurements using the frequency counter are made manually instead of automatically, ΔC_{o1} and ΔF_{o1} can be adjusted to zero by means of the adjusting capacitor C1, and the expression for $\frac{\Delta C_{a1}}{C}$ will be very much simplified.

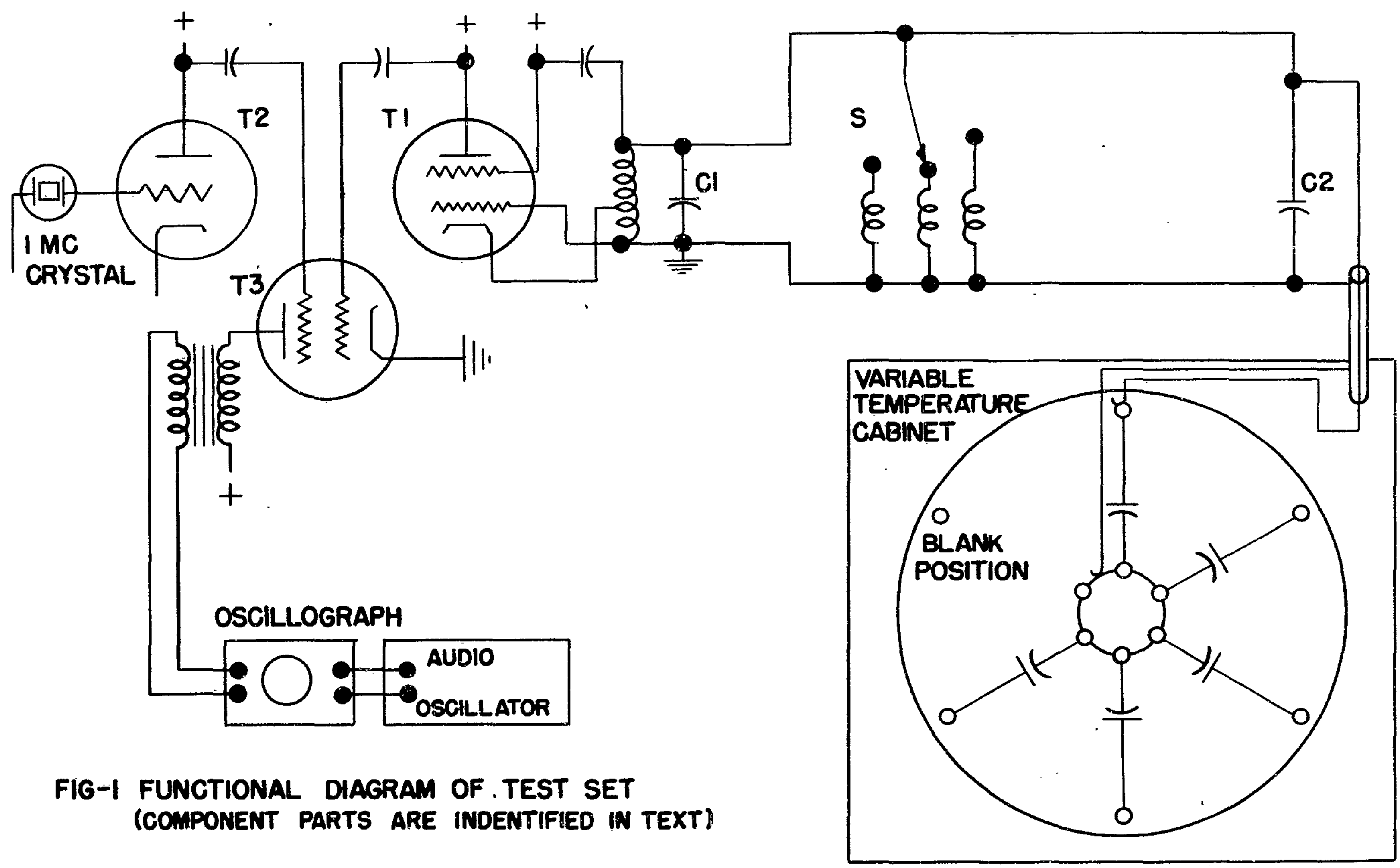


FIG-I FUNCTIONAL DIAGRAM OF TEST SET
(COMPONENT PARTS ARE INDENTIFIED IN TEXT)

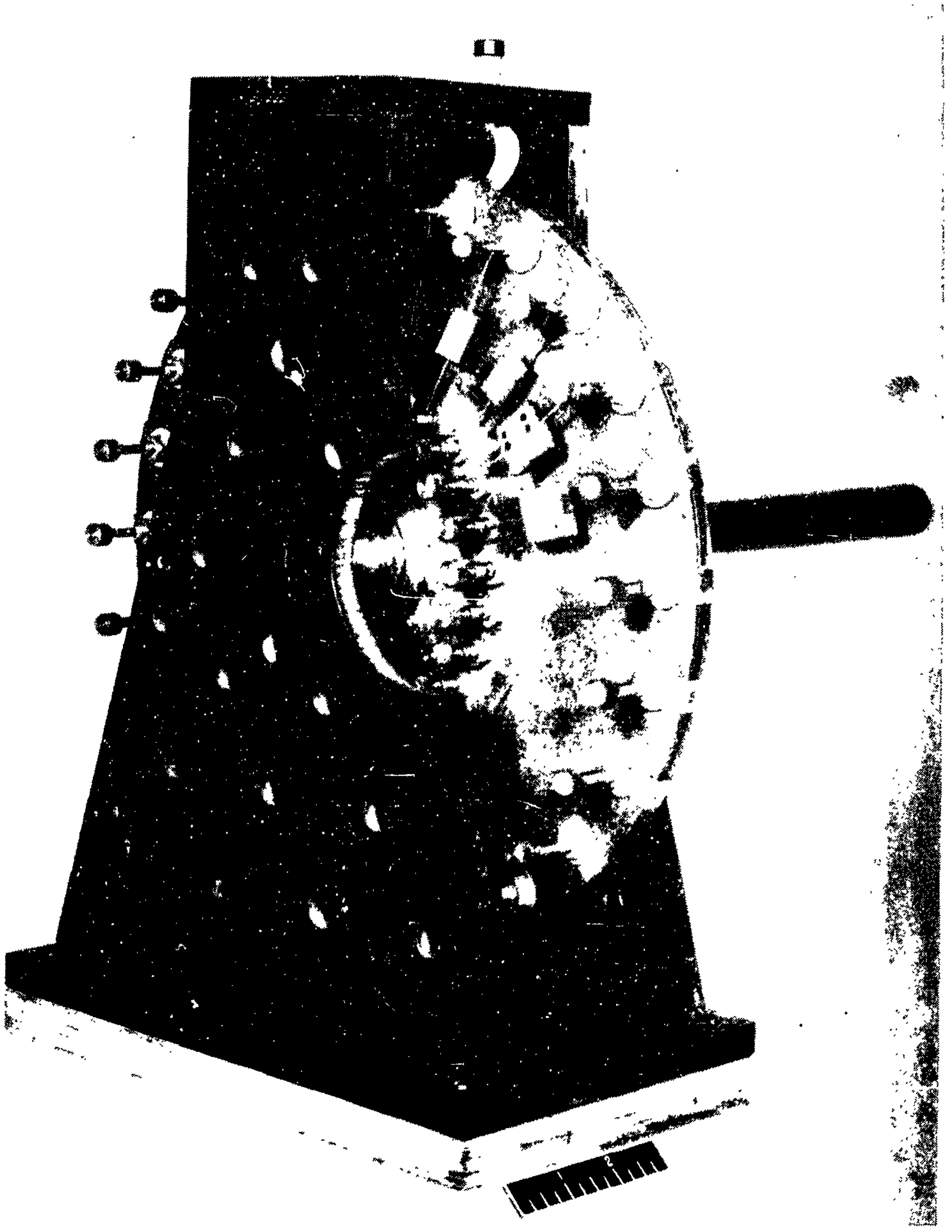


FIGURE 2 - SAMPLE HOLDER, TEST SET I, DESCRIBED IN TECH. MEMO. NO. M1165

FIGURE 2A - POSITION LOCATING MECHANISM OF SAMPLE HOLDER SHOWN IN FIG. 2

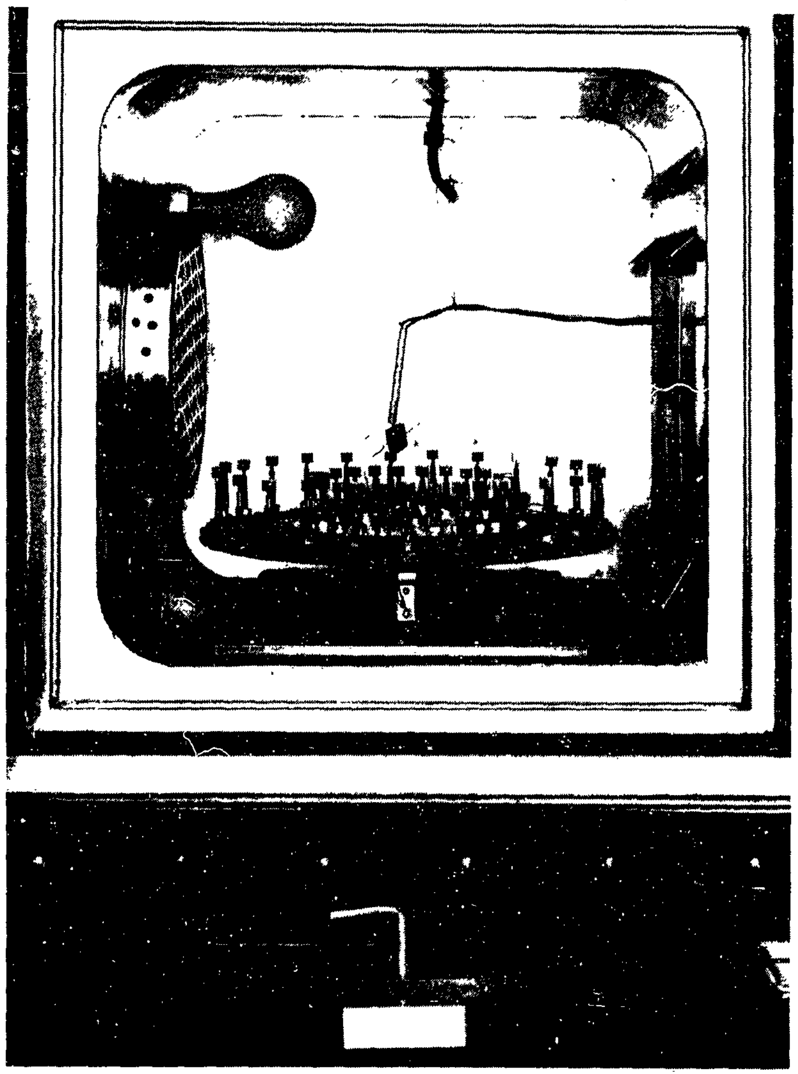


FIGURE 3 - CLOSE-UP OF SAMPLE HOLDER AND POSITION LOCATING MECHANISM, TEST SET II, DESCRIBED IN TECH. MEMO. NO. M1165

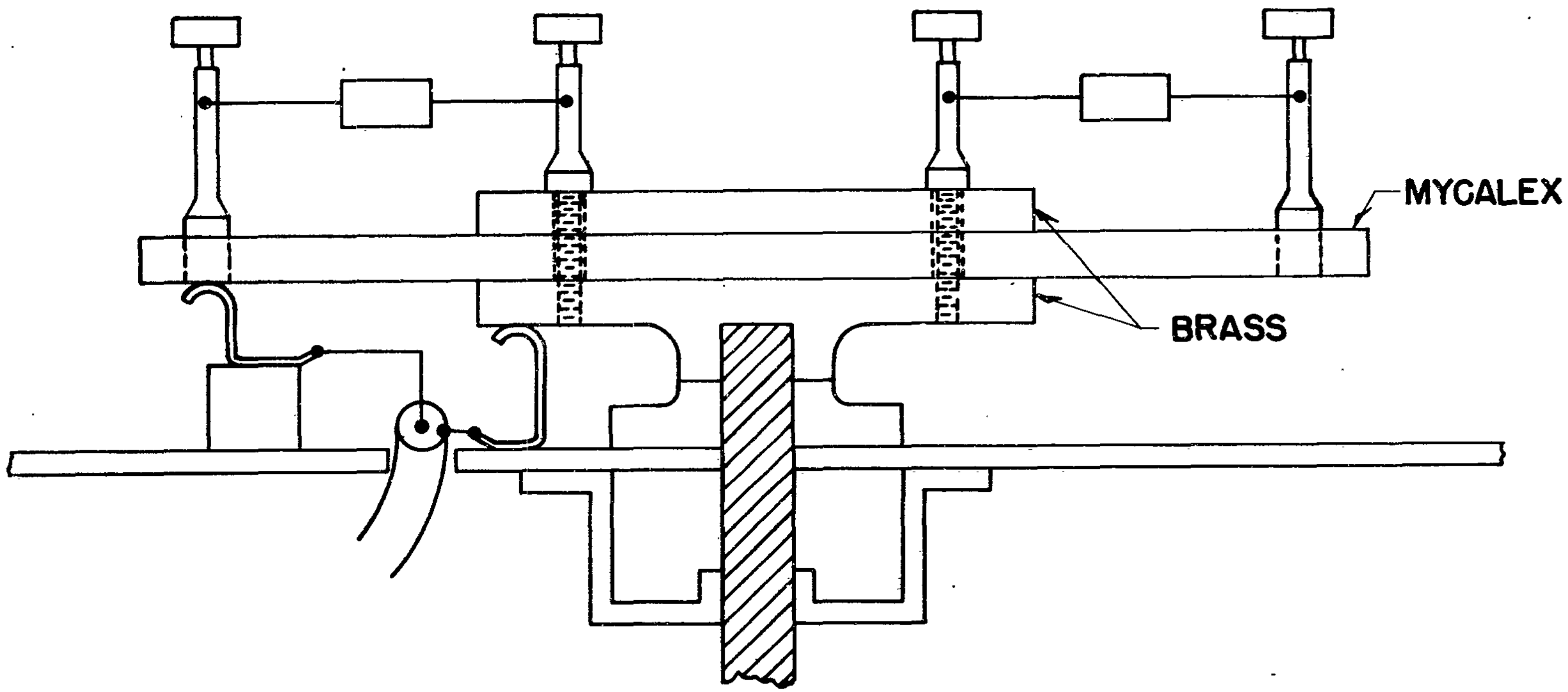
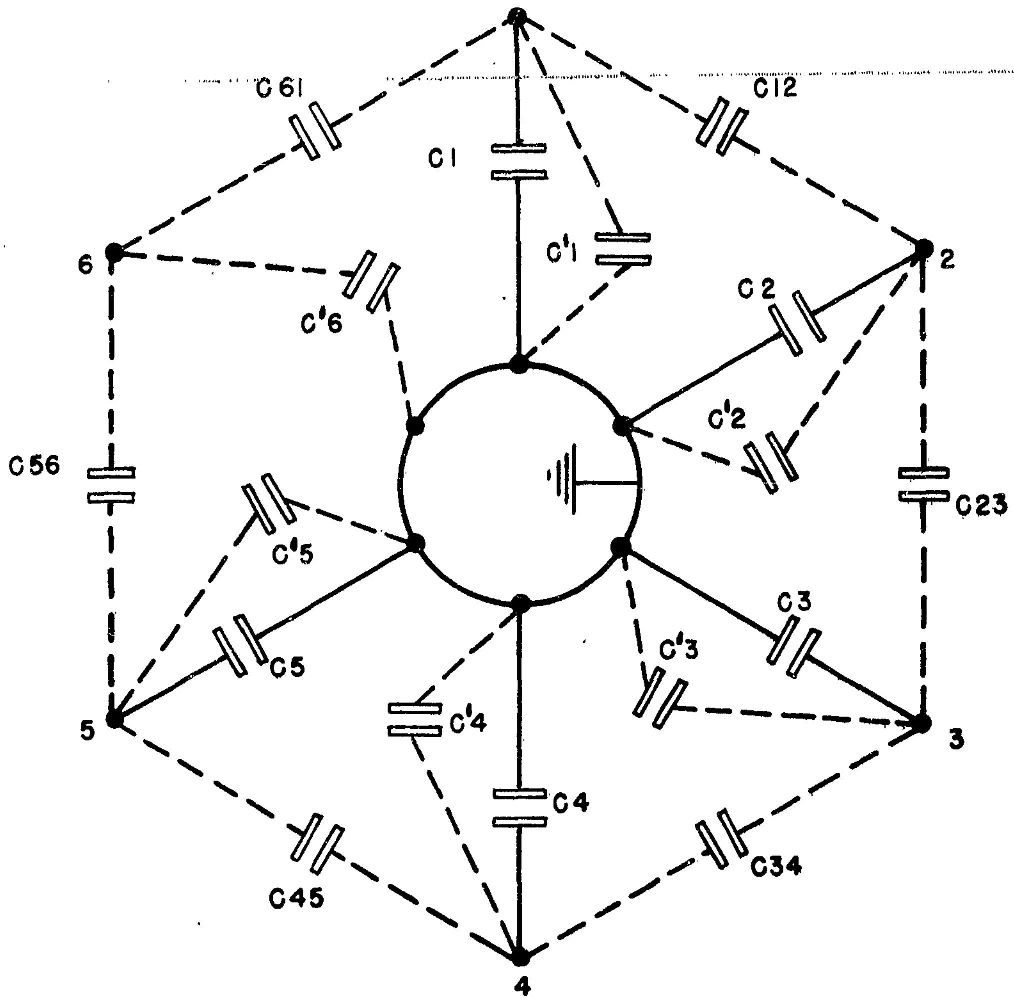


FIG 4: SCHEMATIC DRAWING OF SAMPLE HOLDER SHOWN IN FIG 3.



C1 TO C5 TEST CAPACITORS

C'1 TO C'6 STRAY CAPACITY BETWEEN HIGH AND GROUND TERMINALS OF A POSITION

C12 TO C61 STRAY CAPACITY BETWEEN ADJACENT HIGH TERMINALS

FIG. 5 - STRAY CAPACITIES IN SAMPLE HOLDER

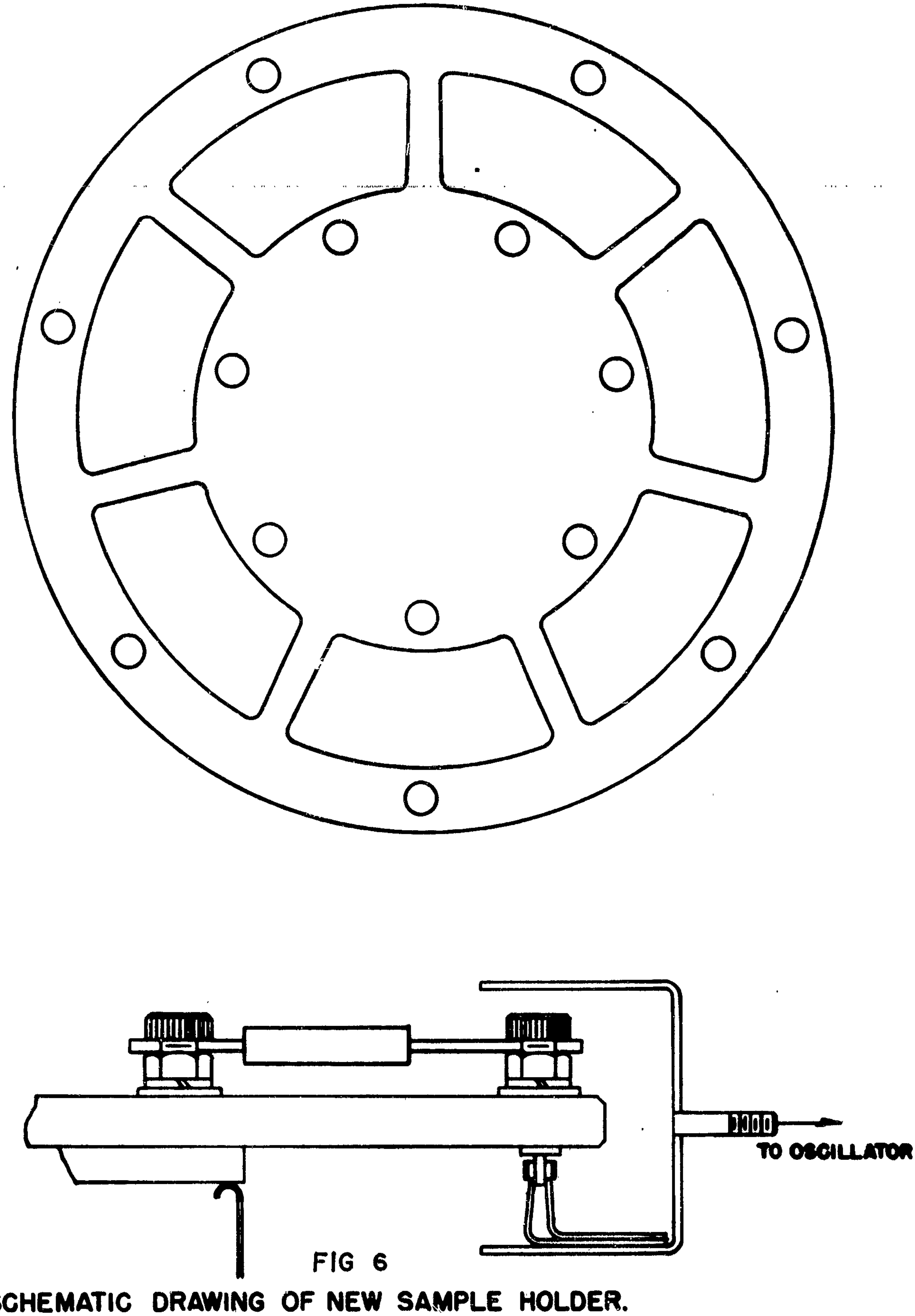


FIG 6

SCHEMATIC DRAWING OF NEW SAMPLE HOLDER.

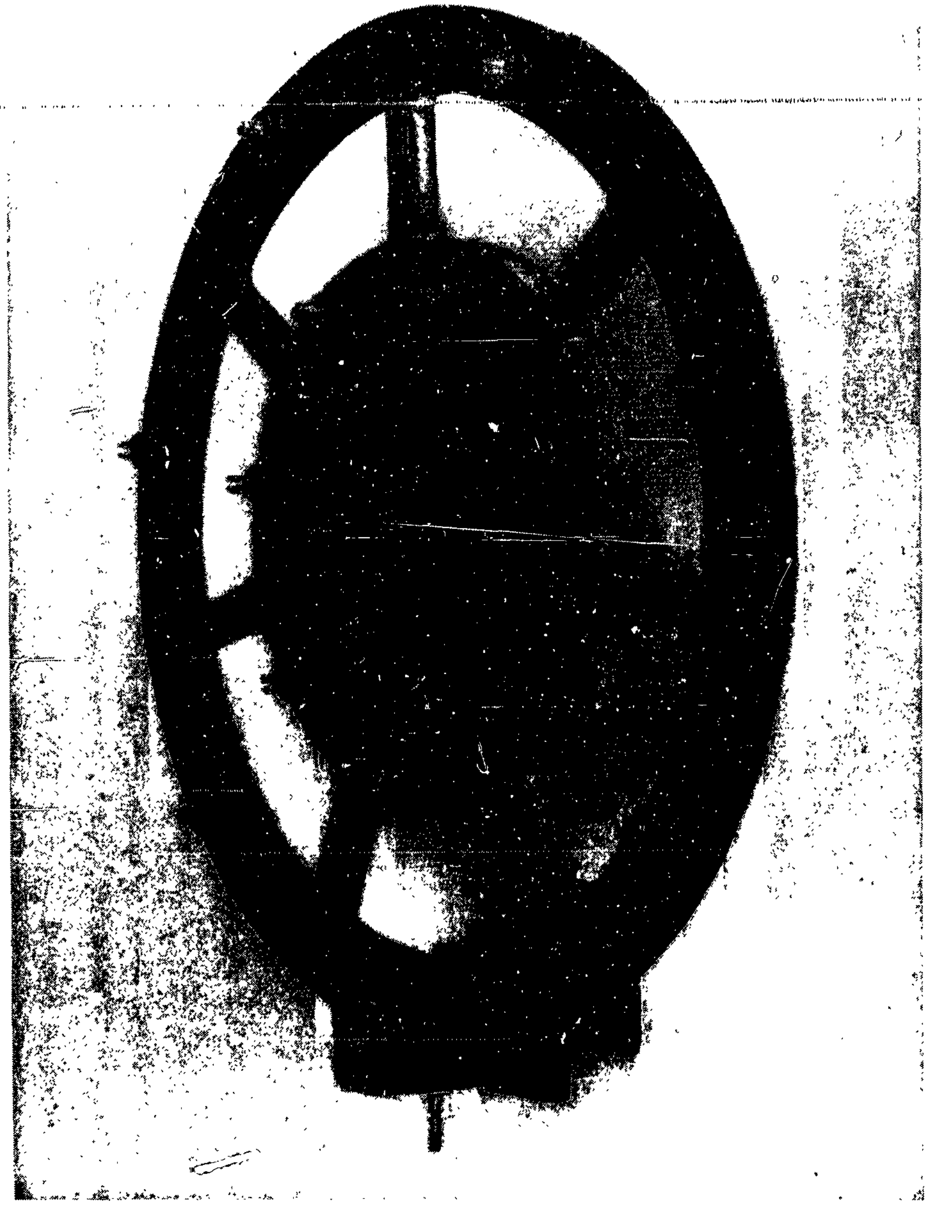


FIGURE 7 UNCLASSIFIED

SAMPLE HOLDER and SHIELD, USED for PRECISE MEASUREMENT of TEMPERATURE COEFFICIENT of CAPACITANCE
Overall 3/4 View . Showing Mounting of Units

DATE 2-12-51 SIGNAL CORPS ENGINEERING LABORATORIES NO. SCEL 29976-X

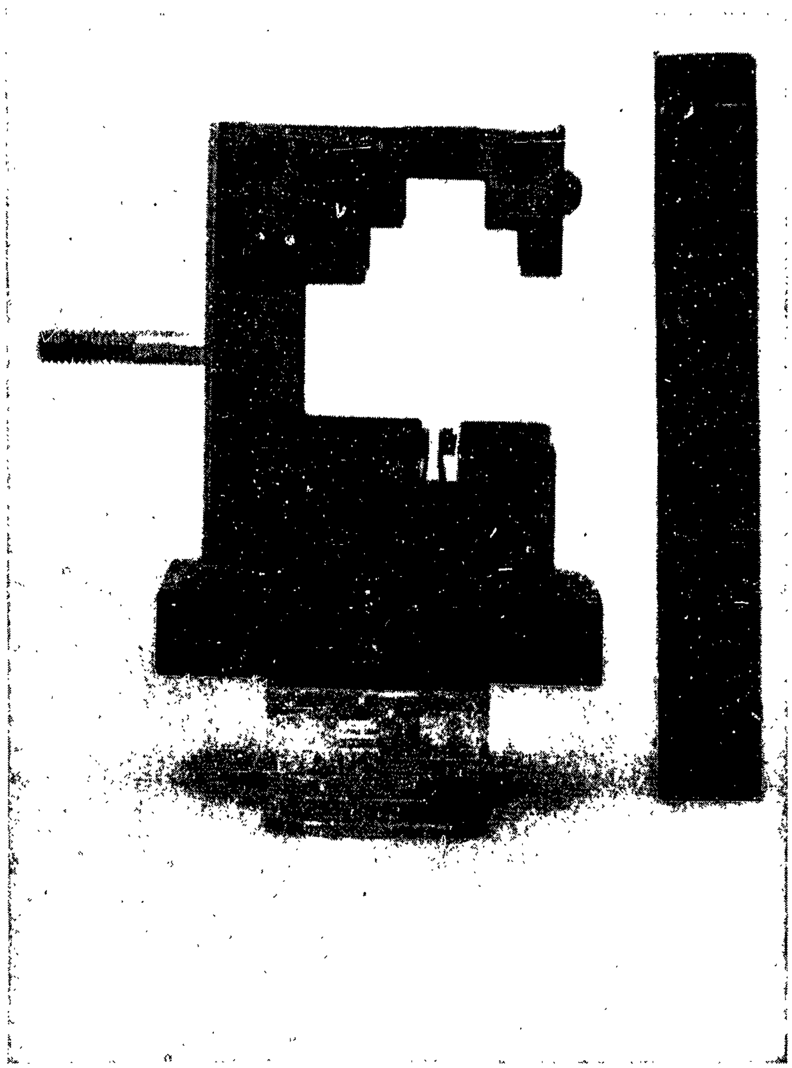


FIGURE 8 *UNCLASSIFIED*

SHIELD USED in PRECISE MEASUREMENT of TEMPERATURE COEFFICIENT of CAPACITANCE

Close-up View

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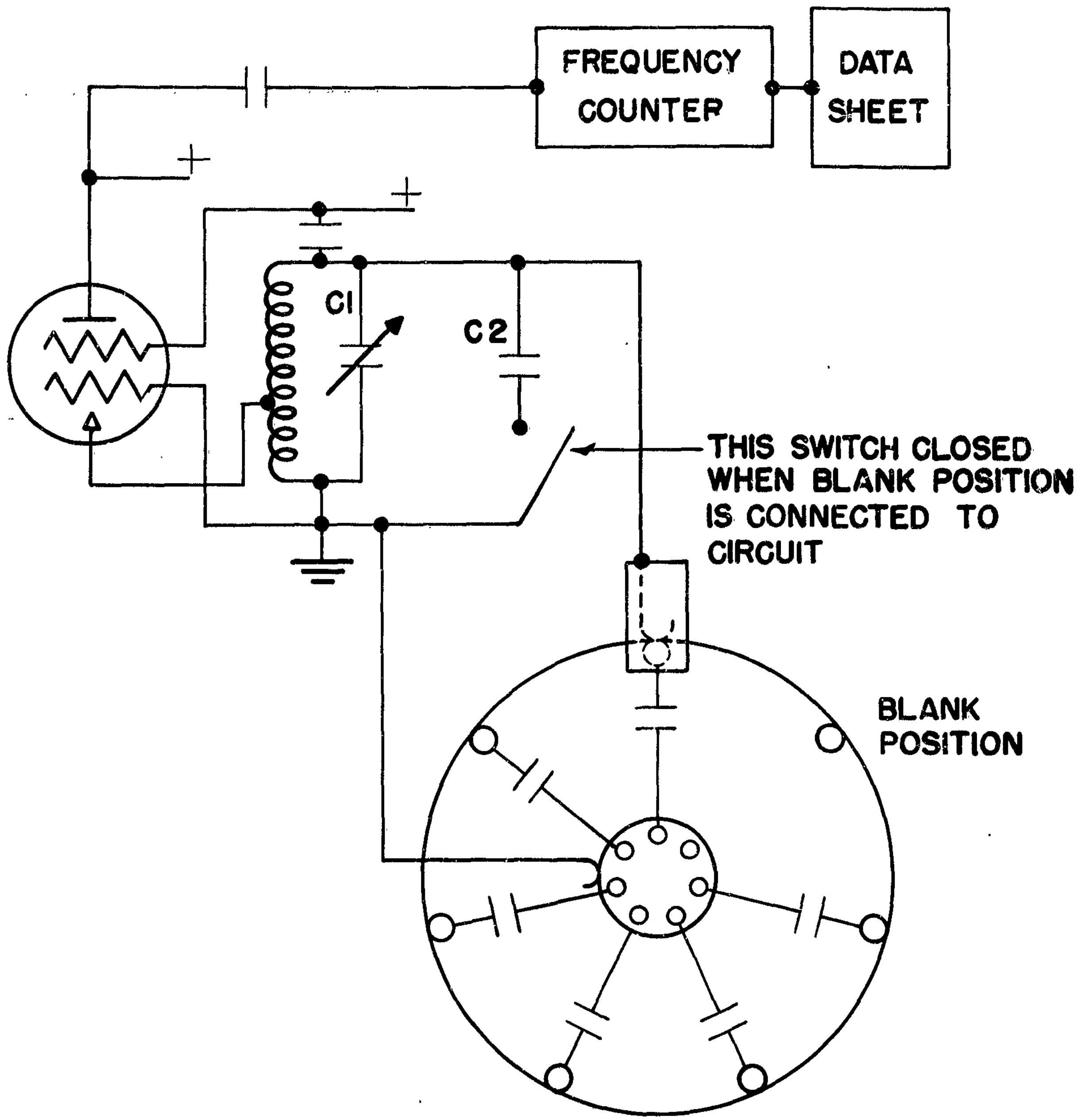

FIG 9. SCHEMATIC DIAGRAM FOR AUTOMATIC MEASUREMENT OF TEMPERATURE COEFFICIENT OF CAPACITANCE